

Notes for *Foundations of Modern Analysis* by
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Chapter 1 – Measure Theory

Section 1.1 – Rings and Algebras

Problems

1.1.1

$$\left(\varliminf_n E_n \right)^c = \overline{\varliminf_n E_n^c}, \quad \left(\overline{\varliminf_n E_n} \right)^c = \varliminf_n E_n^c.$$

Solution. Note that

$$\begin{aligned} x \in \varliminf_n E_n &\iff x \in E_n \text{ for all but finitely many } n \\ &\iff x \in E_n^c \text{ for only finitely many } n. \end{aligned}$$

Hence

$$\begin{aligned} x \in \left(\varliminf_n E_n \right)^c &\iff x \in E_n^c \text{ for infinitely many } n \\ &\iff x \in \overline{\varliminf_n E_n^c}, \end{aligned}$$

proving the first identity.

Next, let $F_n = E_n^c$ for every n . Then

$$\overline{\varliminf_n E_n} = \overline{\varliminf_n F_n^c} = \left(\varliminf_n F_n \right)^c = \left(\varliminf_n E_n^c \right)^c$$

by the first identity, and the second identity follows.

1.1.2

$$\overline{\varliminf_n E_n} = \bigcap_{k=1}^{\infty} \bigcup_{n=k}^{\infty} E_n, \quad \varliminf_n E_n = \bigcup_{k=1}^{\infty} \bigcap_{n=k}^{\infty} E_n.$$

Solution. Suppose $x \in \overline{\lim}_n E_n$. Then $x \in E_n$ for infinitely many n . It follows that $x \in \bigcup_{n=k}^{\infty} E_n$ for all $k \in \mathbb{N}$, and hence that $x \in \bigcap_{k=1}^{\infty} \bigcup_{n=k}^{\infty} E_n$.

Conversely, assume that $x \in \bigcap_{k=1}^{\infty} \bigcup_{n=k}^{\infty} E_n$. Then $x \in \bigcup_{n=k}^{\infty} E_n$ for all $k \in \mathbb{N}$. It follows that $x \in E_n$ for infinitely many n , and thus that $x \in \overline{\lim}_n E_n$. This proves the first identity.

Next, suppose that $x \in \underline{\lim}_n E_n$. Then $x \in E_n$ for all but finitely many n , so there is some $k' \in \mathbb{N}$ such that $x \in E_n$ for all $n \geq k'$. It follows that $x \in \bigcap_{n=k'}^{\infty} E_n$, and hence that $x \in \bigcup_{k=1}^{\infty} \bigcap_{n=k}^{\infty} E_n$.

Conversely, assume that $x \in \bigcup_{k=1}^{\infty} \bigcap_{n=k}^{\infty} E_n$. Then $x \in \bigcap_{n=k'}^{\infty} E_n$ for some $k' \in \mathbb{N}$, which means that $x \in E_n$ for all $n \geq k'$. It follows that $x \in E_n$ for all but finitely many n ; that is, $x \in \underline{\lim}_n E_n$.

1.1.3

If \mathcal{R} is a σ -ring and $E_n \in \mathcal{R}$, then

$$\bigcap_{n=1}^{\infty} E_n \in \mathcal{R}, \quad \overline{\lim}_n E_n \in \mathcal{R}, \quad \underline{\lim}_n E_n \in \mathcal{R}.$$

Solution. Let $Y = \bigcup_{n=1}^{\infty} E_n \in \mathcal{R}$. Then $E_n \subset Y$ for all n , and it follows that

$$\bigcap_{n=1}^{\infty} E_n = Y \cap \left(\bigcap_{n=1}^{\infty} E_n \right) = Y - \left(Y - \bigcap_{n=1}^{\infty} E_n \right).$$

Notice that

$$Y - \bigcap_{n=1}^{\infty} E_n = \bigcup_{n=1}^{\infty} (Y - E_n) \in \mathcal{R},$$

by properties (b) and (e). (The equality is analogous to the identity (1.1.2), but with Y in place of X .) It follows (by (b) again) that $\bigcap_{n=1}^{\infty} E_n \in \mathcal{R}$. For later reference, let us call this result (x).

Given $k \in \mathbb{N}$, let $A_n = \emptyset$ for $n < k$, and let $A_n = E_n$ for $n \geq k$. Then $A_n \in \mathcal{R}$ for all n by (a), hence

$$\bigcup_{n=k}^{\infty} E_n = \bigcup_{n=1}^{\infty} A_n \in \mathcal{R}$$

by (e). It then follows by (x) that

$$\overline{\lim}_n E_n = \bigcap_{k=1}^{\infty} \bigcup_{n=k}^{\infty} E_n \in \mathcal{R}.$$

By a similar argument we find that (x) implies

$$\bigcap_{n=k}^{\infty} E_n \in \mathcal{R}$$

for all $k \in \mathbb{N}$. Thus

$$\varliminf_n E_n = \bigcup_{k=1}^{\infty} \bigcap_{n=k}^{\infty} E_n \in \mathcal{R}$$

by (e).

1.1.4

The intersection of any collection of rings (algebras, σ -rings, or σ -algebras) is also a ring (an algebra, σ -ring, or σ -algebra).

Solution. Let \mathcal{C} be a collection of classes. Let $\bigcap \mathcal{C}$ denote the intersection of all classes in \mathcal{C} . We will show that if one of the properties (a)-(e) is satisfied by all classes in \mathcal{C} , then $\bigcap \mathcal{C}$ satisfies that property as well. The result requested in the problem then follows as an immediate corollary.

It is clear that if every $\mathcal{R} \in \mathcal{C}$ satisfies (a), then so does $\bigcap \mathcal{C}$. Suppose every $\mathcal{R} \in \mathcal{C}$ satisfies (b). If $A, B \in \bigcap \mathcal{C}$ then $A, B \in \mathcal{R}$ for every $\mathcal{R} \in \mathcal{C}$. Hence $A - B \in \mathcal{R}$ for all $\mathcal{R} \in \mathcal{C}$, and it follows that $A - B \in \bigcap \mathcal{C}$. The argument for (c) is similar (with $A \cup B$ in place of $A - B$), and (d) is obvious.

Finally, suppose that every $\mathcal{R} \in \mathcal{C}$ satisfies (e). If $A_1, A_2, \dots \in \bigcap \mathcal{C}$ then $A_1, A_2, \dots \in \mathcal{R}$ for every $\mathcal{R} \in \mathcal{C}$. Hence $\bigcup_{n=1}^{\infty} A_n \in \mathcal{R}$ for all $\mathcal{R} \in \mathcal{C}$, and it follows that $\bigcup_{n=1}^{\infty} A_n \in \bigcap \mathcal{C}$.

1.1.5

If \mathcal{D} is any class of sets, then there exists a unique ring \mathcal{R}_0 such that (i) $\mathcal{R}_0 \supset \mathcal{D}$, and (ii) any ring \mathcal{R} containing \mathcal{D} contains also \mathcal{R}_0 . \mathcal{R}_0 is called the *ring generated by \mathcal{D}* , and is denoted by $\mathcal{R}(\mathcal{D})$.

Solution. Let \mathcal{R}_0 be the intersection of all rings containing \mathcal{D} . This is a ring by the previous exercise, and it satisfies the properties (i) and (ii). To see that it is unique, let \mathcal{R}'_0 also be a ring satisfying (i) and (ii). Then $\mathcal{R}_0 \subset \mathcal{R}'_0$ and $\mathcal{R}'_0 \subset \mathcal{R}_0$ by property (ii), so $\mathcal{R}_0 = \mathcal{R}'_0$.

1.1.6

If \mathcal{D} is any class of sets, then there exists a unique σ -ring \mathcal{S}_0 such that (i) $\mathcal{S}_0 \supset \mathcal{D}$, and (ii) any σ -ring containing \mathcal{D} contains also \mathcal{S}_0 . We call \mathcal{S}_0 the *σ -ring generated by \mathcal{D}* , and denote it by $\mathcal{S}(\mathcal{D})$. A similar result holds for σ -algebras, and we speak of the *σ -algebra generated by \mathcal{D}* .

Solution. By the same argument as in the previous exercise, \mathcal{S}_0 is the intersection of all σ -rings containing \mathcal{D} . Similarly the σ -algebra generated by \mathcal{D} is the intersection of all σ -algebras containing \mathcal{D} .

1.1.7

If \mathcal{D} is any class of sets, then every set in $\mathcal{R}(\mathcal{D})$ can be covered by (that is, is contained in) a finite union of sets of \mathcal{D} . [*Hint:* The class \mathcal{K} of sets that can be covered by finite unions of sets of \mathcal{D} forms a ring.]

Solution. Let \mathcal{K} be the class of all sets that can be covered by a finite union of sets in \mathcal{D} . Certainly $\emptyset \in \mathcal{K}$, since \emptyset is a subset of the empty union. If $A, B \in \mathcal{K}$, then

$$A \subset \bigcup_{i=1}^m E_i, \quad B \subset \bigcup_{i=1}^n F_i,$$

for some sets $E_1, \dots, E_m, F_1, \dots, F_n \in \mathcal{D}$. (Note that m or n can be zero, in which case the corresponding union is empty.) Thus

$$A - B \subset A \subset \bigcup_{i=1}^m E_i$$

and

$$A \cup B \subset \left(\bigcup_{i=1}^m E_i \right) \cup \left(\bigcup_{j=1}^n F_j \right),$$

so both $A - B$ and $A \cup B$ are elements of \mathcal{K} .

The above shows that \mathcal{K} is a ring, and certainly $\mathcal{D} \subset \mathcal{K}$. Hence $\mathcal{R}(\mathcal{D}) \subset \mathcal{K}$ by Problem 1.1.5, and it follows that every set in $\mathcal{R}(\mathcal{D})$ can be covered by a finite union of sets in \mathcal{D} .

Section 1.1 – Definition of Measure

Problems

1.2.1

If μ satisfies the properties (i)-(iii) in Definition 1.2.1, and if $\mu(E) < \infty$ for at least one set E , then (iv) is also satisfied.

Solution. We have

$$\mu(E) = \mu(E \cup \emptyset) = \mu(E) + \mu(\emptyset),$$

hence $\mu(\emptyset) = 0$.

1.2.2

Let X be an infinite space. Let \mathcal{A} be the class of all subsets of X . Define $\mu(E) = 0$ if E is finite and $\mu(E) = \infty$ if E is infinite. Then μ is finitely additive but not completely additive.

Solution. Suppose $A, B \in \mathcal{A}$. Note that $A \cup B$ is finite if both A and B are finite, but infinite otherwise. Hence

$$\mu(A \cup B) = 0 = \mu(A) + \mu(B)$$

in the former case, and

$$\mu(A \cup B) = \infty = \mu(A) + \mu(B)$$

in the latter. This proves that μ is additive; *finite* additivity follows by a simple induction argument.

Let (x_n) be a sequence of distinct points in X . Then $\bigcup_{n=1}^{\infty} \{x_n\}$ is an infinite set, so

$$\mu\left(\bigcup_{n=1}^{\infty} \{x_n\}\right) = \infty,$$

but

$$\sum_{n=1}^{\infty} \mu(\{x_n\}) = 0.$$

Thus μ is not completely additive.

1.2.3

If μ is a measure on a σ -algebra \mathcal{A} , and if E, F are sets of \mathcal{A} , then

$$\mu(E) + \mu(F) = \mu(E \cup F) + \mu(E \cap F).$$

Solution. If $\mu(F) = \infty$, then $\mu(E \cup F) = \infty$ by Theorem 1.2.1(i), and the given equality holds. If $\mu(F) < \infty$, then

$$\begin{aligned} \mu(E \cup F) &= \mu[E \cup (F - (E \cap F))] \\ &= \mu(E) + \mu[F - (E \cap F)] \\ &= \mu(E) + \mu(F) - \mu(E \cap F), \end{aligned}$$

with the last equality following from Theorem 1.2.1(ii). Note that $E \cap F \subset F$ so that $\mu(E \cap F) \leq \mu(F) < \infty$. Hence we can rearrange the above to yield

$$\mu(E) + \mu(F) = \mu(E \cup F) + \mu(E \cap F).$$

1.2.6

Give an example of a measure μ and a monotone-decreasing sequence $\{E_n\}$ of \mathcal{A} such that $\mu(E_n) = \infty$ for all n , and $\mu(\lim_n E_n) = 0$.

Solution. Let $X = \mathbb{R}$ and let $\mathcal{A} = \mathcal{P}(\mathbb{R})$ (the power set of \mathbb{R} ; this is easily seen to be a σ -algebra). Define $\mu : \mathcal{A} \rightarrow [0, \infty]$ such that $\mu(E)$ is the number of points in E (with $\mu(E) = \infty$ if E is infinite). This is easily seen to be a measure.

For each $n \in \mathbb{N}$, let $E_n = (0, 1/n)$. Then (E_n) is a monotone decreasing sequence of sets in \mathcal{A} , $\mu(E_n) = \infty$ for all n , and

$$\mu\left(\lim_n E_n\right) = \mu\left(\bigcap_{n=1}^{\infty} E_n\right) = \mu(\emptyset) = 0.$$

Section 1.3 – Outer Measure

Problems

1.3.1

Define $\mu^*(E)$ as the number of points in E if E is finite and $\mu^*(E) = \infty$ if E is infinite. Show that μ^* is an outer measure. Determine the measurable sets.

Solution. Of the properties listed in Definition 1.3.1, only countable subadditivity is non-obvious for μ^* . But let us start with proving finite subadditivity.

Let A and B be sets. If either is infinite, then so is $A \cup B$, hence

$$\mu^*(A \cup B) = \infty = \mu^*(A) + \mu^*(B).$$

If both A and B are finite sets, then

$$\mu^*(A \cup B) = \mu^*(A) + \mu^*(B - A) \leq \mu^*(A) + \mu^*(B)$$

by basic set-theoretic considerations. Thus μ^* is subadditive, and finite subadditivity follows by induction on the number of sets in the union.

Now, let (E_n) be a sequence of sets. If infinitely many of the sets E_n are nonempty, then $\sum_n \mu^*(E_n) = \infty$, and

$$\mu^*\left(\bigcup_n E_n\right) \leq \sum_n \mu^*(E_n)$$

follows. If only finitely many of the sets E_n are nonempty, let $E_{n_1}, E_{n_2}, \dots, E_{n_k}$ be those sets. Then

$$\mu^*\left(\bigcup_{n=1}^{\infty} E_n\right) = \mu^*\left(\bigcup_{i=1}^k E_{n_i}\right) \leq \sum_{i=1}^k \mu^*(E_{n_i}) = \sum_{n=1}^{\infty} \mu^*(E_n),$$

by finite subadditivity. This proves that μ^* is countably subadditive, and hence that μ^* is an outer measure.

Note that μ^* is *additive* on disjoint sets; if $A \cap B = \emptyset$, then $\mu^*(A \cup B) = \mu^*(A) + \mu^*(B)$. In particular,

$$\mu^*(A) = \mu^*(A \cap E) + \mu^*(A - E)$$

for all sets A, E . That is, all sets are measurable.

1.3.2

Define $\mu^*(\emptyset) = 0$, $\mu^*(E) = 1$ if $E \neq \emptyset$. Show that μ^* is an outer measure, and determine the measurable sets.

Solution. As in the previous exercise, the only slightly non-obvious property is countable subadditivity. Hence, let (E_n) be a sequence of sets. If all the sets E_n are empty, then certainly

$$\mu^*\left(\bigcup_n E_n\right) = 0 = \sum_n \mu^*(E_n).$$

If not, then there is some m such that $E_m \neq \emptyset$, and it follows that

$$\mu^*\left(\bigcup_n E_n\right) = 1 = \mu^*(E_m) \leq \sum_n \mu^*(E_n).$$

Thus μ^* is indeed countably subadditive, and therefore also an outer measure.

The empty set is measurable:

$$\mu^*(A \cap \emptyset) + \mu^*(A - \emptyset) = \mu^*(\emptyset) + \mu^*(A) = \mu^*(A)$$

for all sets A . It follows by Theorem 1.3.1 that X is measurable as well (the measurable sets make up a σ -algebra). Indeed \emptyset and X are the only measurable sets. To see this, let E be any set other than those two (this requires that X contains at least two elements). Then both E and E^c are nonempty, so

$$\mu^*(X \cap E) + \mu^*(X - E) = \mu^*(E) + \mu^*(E^c) = 2 > 1 = \mu^*(X).$$

Section 1.4 – Construction of Outer Measures

Problems

1.4.4

If \mathcal{K} is a σ -algebra and λ is a measure on \mathcal{K} , then $\mu^*(A) = \lambda(A)$ for any $A \in \mathcal{K}$. [*Hint:* $\mu^*(A) = \inf\{\lambda(E); E \in \mathcal{K}, E \supset A\}$.]

Solution. Note that the description of μ^* can be simplified when \mathcal{K} is a σ -algebra and λ is a measure. For suppose that $A \subset X$, $E_n \in \mathcal{K}$ ($n = 1, 2, \dots$), and $A \subset \bigcup_n E_n$. Then $E := \bigcup_n E_n \in \mathcal{K}$, and $\lambda(E) \leq \sum_n \lambda(E_n)$ by Theorem 1.2.2. Hence

$$\mu^*(A) = \inf\{\lambda(E); E \in \mathcal{K}, E \supset A\}.$$

Now, suppose that $A \in \mathcal{K}$. Certainly $\lambda(A)$ is an element of $\{\lambda(E); E \in \mathcal{K}, E \supset A\}$. And if $E \in \mathcal{K}$ and $E \supset A$, then $\lambda(E) \geq \lambda(A)$ by Theorem 1.2.1(i). Thus

$$\lambda(A) = \inf\{\lambda(E); E \in \mathcal{K}, E \supset A\} = \mu^*(A).$$

1.4.5

If \mathcal{K} is a σ -algebra and λ is a measure on \mathcal{K} , then every set in \mathcal{K} is μ^* -measurable.

Solution. Recall the simplified description of μ^* from the previous problem. Let $E \in \mathcal{K}$ and $A \subset X$. For every $\epsilon > 0$ there exists $F \in \mathcal{K}$ such that $F \supset A$ and

$$\mu^*(A) + \epsilon > \lambda(F);$$

else $\mu^*(A)$ would not be the greatest lower bound of $\{\lambda(E); E \in \mathcal{K}, E \supset A\}$. Moreover,

$$\lambda(F) = \lambda(F \cap E) + \lambda(F - E)$$

since λ is a measure on \mathcal{K} ,

$$\lambda(F \cap E) + \lambda(F - E) = \mu^*(F \cap E) + \mu^*(F - E)$$

by what we found in the previous exercise, and finally

$$\mu^*(F \cap E) + \mu^*(F - E) \geq \mu^*(A \cap E) + \mu^*(A - E)$$

by monotonicity of the outer measure μ^* . Putting all of this together, we have

$$\mu^*(A) + \epsilon > \mu^*(A \cap E) + \mu^*(A - E)$$

for all $\epsilon > 0$, and thus

$$\mu^*(A) \geq \mu^*(A \cap E) + \mu^*(A - E).$$

It follows that every set $E \in \mathcal{K}$ is μ^* -measurable.

Section 1.6 – The Lebesgue and the Lebesgue-Stieltjes Measures

Problems

1.6.3

The outer Lebesgue measure of a closed bounded interval $[a, b]$ on the real line is equal to $b - a$. [*Hint:* Use the Heine-Borel theorem to replace a countable covering by a finite covering.]

Solution. Suppose (E_n) is a sequence of elements of \mathcal{K} (i.e. a sequence of open intervals) such that $[a, b] \subset \bigcup_{n=1}^{\infty} E_n$. The collection $\{E_n\}$ constitutes an *open cover* of $[a, b]$. By the Heine-Borel theorem $[a, b]$ is compact, hence there exists a *finite subcover* $\{E_{n_1}, \dots, E_{n_k}\}$, such that $[a, b] \subset \bigcup_{i=1}^k E_{n_i}$.

Assume without loss of generality that $E_{n_i} \cap [a, b] \neq \emptyset$ for all i ; otherwise we can simply remove those E_{n_i} that are disjoint with $[a, b]$ and still have a finite subcover. Write $E_{n_i} = (a_i, b_i)$ for each i , and define

$$\alpha = \min\{a_1, \dots, a_k\}, \quad \beta = \max\{b_1, \dots, b_k\}.$$

It is clear that α and β are the infimum and supremum, respectively, of $\bigcup_{i=1}^k E_{n_i}$. Note that $\alpha = a_j$ for some j , and $a_j < a < b_j$ since E_{n_j} and $[a, b]$ have nonempty intersection. Thus $(\alpha, a] \subset \bigcup_{i=1}^k E_{n_i}$, and similarly $[b, \beta) \subset \bigcup_{i=1}^k E_{n_i}$. It follows that

$$\bigcup_{i=1}^k E_{n_i} = (\alpha, \beta) \in \mathcal{K}.$$

Finally note that λ is finitely subadditive. (This is easily proven with induction.) (TODO: This is not convincing; use better proof from Rosenthal notes.) Thus,

$$\sum_{n=1}^{\infty} \lambda(E_n) \geq \sum_{i=1}^k \lambda(E_{n_i}) \geq \lambda[(\alpha, \beta)] = \beta - \alpha > b - a.$$

It follows that $b - a$ is a lower bound of the set

$$\Lambda([a, b]) := \left\{ \sum_{n=1}^{\infty} \lambda(E_n); E_n \in \mathcal{K}, \bigcup_{n=1}^{\infty} E_n \supset [a, b] \right\}.$$

Moreover, for every $\epsilon > 0$ we have

$$[a, b] \subset \left(a - \frac{\epsilon}{2}, b + \frac{\epsilon}{2}\right) \in \mathcal{K}$$

and

$$\lambda \left[\left(a - \frac{\epsilon}{2}, b + \frac{\epsilon}{2}\right) \right] = b - a + \epsilon.$$

Hence $b - a$ is the *greatest* lower bound of $\Lambda([a, b])$, and $\mu^*([a, b]) = b - a$.

1.6.4

The outer Lebesgue measure of each of the intervals (a, b) , $[a, b)$, $(a, b]$ is equal to $b - a$.

Solution. Recall that μ^* is monotone, on account of being an outer measure. Hence $\mu^*[(a, b)] \leq \mu^*([a, b]) = b - a$, the latter equality being the result of the previous problem. Moreover, for all $\epsilon \in (0, b - a)$ we have

$$\left(a + \frac{\epsilon}{2}, b - \frac{\epsilon}{2}\right) \subset (a, b),$$

so that

$$\mu^*[(a, b)] \geq \mu^* \left[\left(a + \frac{\epsilon}{2}, b - \frac{\epsilon}{2}\right) \right] = b - a + \epsilon.$$

Thus $\mu^*[(a, b)] \geq b - a$, and it follows that $\mu^*[(a, b)] = b - a$.

The outer measures of $[a, b)$ and $(a, b]$ follow immediately by monotonicity:

$$\mu^*[(a, b)] \leq \mu^*([a, b)) \leq \mu^*([a, b]),$$

so that $\mu^*([a, b)) = b - a$. Similarly for $(a, b]$.

1.6.5

Consider the transformation $Tx = \alpha x + \beta$ from the real line onto itself, where α, β are real numbers and $\alpha \neq 0$. It maps sets E onto sets $T(E)$. Denote by μ (μ^*) the Lebesgue measure (outer measure) on the real line. Prove

- (a) For any set E , $\mu^*(T(E)) = |\alpha|\mu^*(E)$.
- (b) E is Lebesgue-measurable if and only if $T(E)$ is Lebesgue-measurable.
- (c) If E is Lebesgue-measurable, then $\mu(T(E)) = |\alpha|\mu(E)$.

Solution. Let us start with a couple of simple observations:

- T is bijective, with inverse given by

$$T^{-1}(x) = \frac{x - \beta}{\alpha}.$$

- Suppose $I = (a, b)$. Then

$$T(I) = (\alpha a + \beta, \alpha b + \beta)$$

if $\alpha > 0$, and

$$T(I) = (\beta b + \beta, \alpha a + \beta)$$

if $\alpha < 0$. Either way,

$$\mu^*[T(I)] = |\alpha|(b - a) = |\alpha|\mu^*(I),$$

where we have used one of the results of the previous exercise. Similarly, $T^{-1}(I)$ is an open interval and

$$\mu^*[T^{-1}(I)] = |\alpha|^{-1}\mu^*(I).$$

Of course, the latter two identities still hold if $I = \emptyset$. Hence they hold for all $I \in \mathcal{K}$.

Also, let us use the notation

$$\Lambda(E) = \left\{ \sum_{n=1}^{\infty} \lambda(I_n); I_n \in \mathcal{K}, \bigcup_{n=1}^{\infty} I_n \supset E \right\}$$

for all $E \subset \mathbb{R}$.

- (a) Suppose (I_n) is a sequence in \mathcal{K} (i.e. a sequence of open intervals) and $E \subset \bigcup_n I_n$. Then $T(I_n) \in \mathcal{K}$ for every n ,

$$T(E) \subset T\left(\bigcup_n I_n\right) = \bigcup_n T(I_n),$$

and

$$\sum_n \lambda[T(I_n)] = |\alpha| \sum_n \lambda(I_n).$$

Thus, if $s \in \Lambda(E)$, then $|\alpha|s \in \Lambda[T(E)]$. It follows that

$$\mu^*[T(E)] = \inf \Lambda[T(E)] \leq |\alpha| \inf \Lambda(E) = |\alpha| \mu^*(E).$$

Conversely, suppose (J_n) is a sequence in \mathcal{K} and $T(E) \subset \bigcup_n J_n$. Then $T^{-1}(J_n) \in \mathcal{K}$ for all n ,

$$E = T^{-1}[T(E)] \subset T^{-1}\left(\bigcup_n J_n\right) = \bigcup_n T^{-1}(J_n),$$

and

$$\sum_n \lambda[T^{-1}(J_n)] = |\alpha|^{-1} \sum_n \lambda(J_n).$$

Hence, by the same logic as above, we find that $\mu^*(E) \leq |\alpha|^{-1} \mu^*[T(E)]$, and it follows that

$$\mu^*[T(E)] = |\alpha| \mu^*(E).$$

- (b) Note that if $f : X \rightarrow Y$ is a bijective function (between arbitrary sets X, Y), then

$$\begin{aligned} f^{-1}[f(A)] &= A, \\ f(A \cup B) &= f(A) \cup f(B), \\ f(A - B) &= f(A) - f(B), \\ f[f^{-1}(C)] &= C, \end{aligned}$$

for all $A, B \subset X$ and $C \subset Y$.

Suppose that E is measurable:

$$\mu^*(A) = \mu^*(A \cap E) + \mu^*(A - E)$$

for all $A \subset \mathbb{R}$. Then, for all $B \subset \mathbb{R}$, we have

$$\begin{aligned} \mu^*[B \cap T(E)] + \mu^*[B - T(E)] &= \mu^*[T(T^{-1}(B) \cap E)] + \mu^*[T(T^{-1}(B) - E)] \\ &= |\alpha| \mu^*[T^{-1}(B) \cap E] + |\alpha| \mu^*[T^{-1}(B) - E] \\ &= |\alpha| \mu^*[T^{-1}(B)] \\ &= \mu^*(B), \end{aligned}$$

so that $T(E)$ is measurable.

Conversely, suppose that $T(E)$ is measurable. Then, for all $A \subset \mathbb{R}$,

$$\begin{aligned} \mu^*(A \cap E) + \mu^*(A - E) &= \mu^*[T^{-1}(T(A) \cap T(E))] + \mu^*[T^{-1}(T(A) - T(E))] \\ &= |\alpha|^{-1} \mu^*[T(A) \cap T(E)] + |\alpha|^{-1} \mu^*[T(A) - T(E)] \\ &= |\alpha|^{-1} \mu^*[T(A)] \\ &= \mu^*(A), \end{aligned}$$

so that E is measurable.

- (c) This is immediate given (a), (b), and the definition of the Lebesgue-measure. First, $T(E)$ is Lebesgue-measurable by (b). Next, $\mu(E) = \mu^*(E)$ and $\mu[T(E)] = \mu^*[T(E)]$ since μ is simply the restriction of μ^* to the measurable sets. Finally, $\mu^*[T(E)] = |\alpha|\mu^*(E)$ by (a).

Chapter 2 – Integration

Section 2.1 – Definition of Measurable Functions

Problems

2.1.6

The *characteristic function* of a set E is the function χ_E defined by

$$\chi_E(x) = \begin{cases} 1, & \text{if } x \in E, \\ 0, & \text{if } x \notin E. \end{cases}$$

Prove that the set E is measurable if and only if the function χ_E is measurable.

Solution. Suppose $E \in \mathcal{A}$. For all $c \in \mathbb{R}$,

$$\chi_E^{-1}\{(-\infty, c)\} = \{x \in X; \chi_E(x) < c\} = \begin{cases} \emptyset & (c \leq 0), \\ E^c & (0 < c \leq 1), \\ X & (c > 1), \end{cases}$$

so that $\chi_E^{-1}\{(-\infty, c)\} \in \mathcal{A}$. By Theorem 2.1.1, χ_E is measurable.

Conversely, suppose χ_E is measurable. Then E is measurable, since

$$E = X - E^c = \chi^{-1}\{(-\infty, 2)\} - \chi^{-1}\{(-\infty, 1)\}.$$

2.1.9

If f is measurable, then $|f|$ and $|f|^2$ are measurable.

Solution. If $c \leq 0$, then

$$(|f|)^{-1}\{(-\infty, c)\} = (|f|^2)^{-1}\{(-\infty, c)\} = \emptyset \in \mathcal{A},$$

since $|f|$ and $|f|^2$ are nonnegative functions.

Let $c > 0$. Then

$$(|f|)^{-1}\{(-\infty, c)\} = \{x \in X; -c < f(x) < c\} = f^{-1}\{(-c, c)\}.$$

The set $(-c, c)$ is open, hence $f^{-1}\{(-c, c)\} \in \mathcal{A}$ by the measurability of f . Similarly,

$$(|f|^2)^{-1}\{(-\infty, c)\} = f^{-1}\{(-\sqrt{c}, \sqrt{c})\} \in \mathcal{A}.$$

Finally,

$$(|f|)^{-1}\{+\infty\} = (|f|^2)^{-1}\{+\infty\} = f^{-1}\{+\infty\} \cup f^{-1}\{-\infty\} \in \mathcal{A}$$

by the measurability of f , and

$$(|f|)^{-1}\{-\infty\} = (|f|^2)^{-1}\{-\infty\} = \emptyset \in \mathcal{A}$$

since $|f|$ and $|f|^2$ are nonnegative. Thus, both $|f|$ and $|f|^2$ are measurable by Theorem 2.1.1.

2.1.10

A monotone function defined on the real line is Lebesgue-measurable.

Solution. Let f be a monotone increasing extended real-valued function on \mathbb{R} ;

$$(\forall x, y \in \mathbb{R}) : \quad x < y \implies f(x) \leq f(y).$$

Given any $c \in \mathbb{R}$, let

$$\xi_c = \inf\{x \in X; f(x) \geq c\}.$$

We need to consider two cases: $f(\xi_c) < c$ and $f(\xi_c) \geq c$. In the former case, $f(x) < c$ for all $x \leq \xi_c$ and $f(x) \geq c$ for all $x > \xi_c$ (by monotonicity). Hence

$$f^{-1}\{(-\infty, c)\} = (-\infty, \xi_c].$$

This is a Borel set, hence also a Lebesgue set (see Problem 1.9.3). In the latter case, $f(x) < c$ for all $x < \xi_c$ and $f(x) \geq c$ for all $x \geq \xi_c$, so that

$$f^{-1}\{(-\infty, c)\} = (-\infty, \xi_c),$$

which is Lebesgue-measurable. Since c was arbitrary, we conclude that f is measurable, by Theorem 2.1.1.

The proof for f monotone decreasing is similar.

Section 2.2 – Operations on Measurable Functions

Problems

2.2.2

Let $g(u_1, \dots, u_k)$ be a continuous function in \mathbb{R}^k , and let $\varphi_1, \dots, \varphi_k$ be measurable functions. Prove that the composite function $h(x) = g[\varphi_1(x), \dots, \varphi_k(x)]$ is a measurable function. Note that as a special case we may conclude that

$$\max(\varphi, \dots, \varphi_n) \quad \text{and} \quad \min(\varphi, \dots, \varphi_n)$$

are measurable functions.

Solution. We will use the following fact, which may be proven in a course in topology:

\mathbb{R}^k has a countable basis of product open subsets. Hence, if U is an open subset of \mathbb{R}^k , then there are open subsets $U_{ni} \subset \mathbb{R}$ for $n = 1, 2, \dots$ and $i = 1, \dots, k$ such that

$$U = \bigcup_{n=1}^{\infty} (U_{n1} \times \cdots \times U_{nk}).$$

We are assuming that g is real-valued, likewise for the functions φ_i . Let $c \in \mathbb{R}$. Note that $g^{-1}\{(-\infty, c)\}$ is open by continuity of g . Thus

$$g^{-1}\{(-\infty, c)\} = \bigcup_{n=1}^{\infty} (U_{n1} \times \cdots \times U_{nk})$$

for some open subsets $U_{ni} \subset \mathbb{R}$. Hence

$$\begin{aligned} h^{-1}\{(-\infty, c)\} &= \{x \in X; g(\varphi_1(x), \dots, \varphi_k(x)) \leq c\} \\ &= \{x \in X; (\varphi_1(x), \dots, \varphi_k(x)) \in g^{-1}\{(-\infty, c)\}\} \\ &= \bigcup_{n=1}^{\infty} \{x \in X; (\varphi_1(x), \dots, \varphi_k(x)) \in U_{n1} \times \cdots \times U_{nk}\} \\ &= \bigcup_{n=1}^{\infty} \bigcap_{i=1}^k \{x \in X; \varphi_i(x) \in U_{ni}\} \\ &= \bigcup_{n=1}^{\infty} \bigcap_{i=1}^k \varphi_i^{-1}(U_{ni}). \end{aligned}$$

The sets $\varphi_i(U_{ni})$ are measurable since the functions φ_i are measurable. It follows that $h^{-1}\{(-\infty, c)\}$ is measurable, and thus that h is measurable, by Theorem 2.1.1.

To apply the above to the max and min functions $\mathbb{R}^k \rightarrow \mathbb{R}$ we must show that they are continuous. Let $a < b$ and note that

$$\begin{aligned} \max^{-1}\{(a, b)\} &= \{(x_1, \dots, x_k) \in \mathbb{R}^k; x_i > a \text{ for some } i\} \\ &\cap \{(x_1, \dots, x_k) \in \mathbb{R}^k; x_i < b \text{ for all } i\}. \end{aligned}$$

Both sets in the above binary intersection are easily seen to be open by considering ϵ -neighborhoods about their points. It follows that $\max^{-1}(U)$ is open for all open subsets $U \in \mathbb{R}^k$, since every such U can be written as a countable union of open intervals. Thus max is continuous, and one similarly shows that min is continuous.

2.2.3

Let $f(x)$ be a measurable function and define

$$g(x) = \begin{cases} \frac{1}{f(x)}, & \text{if } f(x) \neq 0, \\ 0, & \text{if } f(x) = 0. \end{cases}$$

Prove that g is measurable.

Solution. For $c < 0$,

$$g^{-1}\{(-\infty, c)\} = \{x; 1/f(x) < c\} = \{x; 1/c < f < 0\} = f^{-1}\{(1/c, 0)\},$$

which is measurable by the measurability of f . Next,

$$g^{-1}\{(-\infty, 0)\} = \{x; 1/f(x) < 0\} = \{x; f(x) < 0\} = f^{-1}\{(-\infty, 0)\},$$

also measurable. Note that if we take the natural convention (unfortunately not addressed in the text) that $x/(\pm\infty) = 0$ for all $x \in \mathbb{R}$, then

$$g^{-1}\{0\} = \{x; f(x) = 0\} \cup \{x; f(x) = \pm\infty\} = f^{-1}\{0\} \cup f^{-1}\{\pm\infty\}.$$

Hence, for $c > 0$,

$$\begin{aligned} g^{-1}\{(0, c)\} &= g^{-1}\{(-\infty, 0)\} \cup g^{-1}\{0\} \cup g^{-1}\{(0, \infty)\} \\ &= f^{-1}\{(-\infty, 0)\} \cup f^{-1}\{0\} \cup f^{-1}\{\pm\infty\} \cup f^{-1}\{(1/c, \infty)\} \\ &= f^{-1}\{(-\infty, 0]\} \cup f^{-1}\{\pm\infty\} \cup f^{-1}\{(1/c, \infty)\}, \end{aligned}$$

which is measurable by the measurability of f (see Problem 2.1.4). Finally, $g^{-1}\{\pm\infty\} = \emptyset$, and it follows by Theorem 2.1.1 that g is measurable.

Section 2.3 – Egoroff's Theorem

Problems

2.3.2

Let $\{f_n\}$ be a sequence of measurable functions in a finite measure space X . Suppose that for almost every x , $\{f_n(x)\}$ is a bounded set. Then for any $\epsilon > 0$ there exist a positive number c and a measurable set E with $\mu(X - E) < \epsilon$, such that $|f_n(x)| \leq c$ for all $x \in E$, $n = 1, 2, \dots$.

Solution. The definition we have for 'bounded set' applies to metric spaces, and it does not make much sense here since the functions f_n may be extended real-valued. Hence we will assume that ' $\{f_n(x)\}$ is a bounded set' means that $\sup_n |f_n(x)| < \infty$.

Let $g = \sup_n |f_n|$, and note that g is measurable by Problem 2.1.9 and Theorem 2.2.3. Let $F = \{x; g(x) < \infty\}$. Notice that $g(x) < \infty$ if and only if $\{f_n(x)\}$ is bounded. Hence $\mu(X - F) = 0$.

For $k = 1, 2, \dots$, define $F_k = \{x; g(x) \leq k\}$. Then $F_1 \subset F_2 \subset \dots$ and $\lim_k F_k = \bigcup_{k=1}^{\infty} F_k = F$. By Theorem 1.2.1(iv),

$$\lim_k \mu(X - F_k) = \mu(X - F) = 0.$$

Given any $\epsilon > 0$, there exists a positive integer K such that $\mu(X - F_k) < \epsilon$ for all $k \geq K$. In particular $\mu(X - F_K) < \epsilon$, and $g(x) \leq K$ for all $x \in F_K$, which means that $|f_n(x)| \leq K$ for all $x \in F_K$.

Section 2.4 – Convergence in Measure

Problems

2.4.3

Prove the following result (which immediately yields another proof of Corollary 2.4.2): Let f_n ($n = 1, 2, \dots$) and f be a.e. real-valued measurable functions in a finite measure space. For any $\epsilon > 0$, $n \geq 1$, let

$$E_n(\epsilon) = \{x; |f_n(x) - f(x)| \geq \epsilon\}.$$

Then $\{f_n\}$ converges a.e. to f if and only if

$$\lim_{n \rightarrow \infty} \mu \left[\bigcup_{m=n}^{\infty} E_m(\epsilon) \right] = 0 \quad \text{for any } \epsilon > 0. \quad (2.4.2)$$

[Hint: Let $F = \{x; \{f_n(x)\} \text{ is not convergent to } f(x)\}$. Then $F = \bigcup_{k=1}^{\infty} \overline{\lim_n E_n(1/k)}$. Show that $\mu(F) = 0$ if and only if (2.4.2) holds.]

Solution. Define

$$F = \bigcup_{k=1}^{\infty} \overline{\lim_n E_n \left(\frac{1}{k} \right)} = \bigcup_{k=1}^{\infty} \bigcap_{n=1}^{\infty} \bigcup_{m=n}^{\infty} E_m \left(\frac{1}{k} \right).$$

Note that

$$\begin{aligned} x \in F &\iff \exists k, \forall n, \exists m \geq n, |f_m(x) - f(x)| \geq \frac{1}{k} \\ &\iff \neg \left(\forall k, \exists n, \forall m \geq n, |f_m(x) - f(x)| < \frac{1}{k} \right) \\ &\iff f_n(x) \not\rightarrow f(x), \end{aligned}$$

so that

$$F = \{x; f_n(x) \not\rightarrow f(x)\}.$$

Suppose (2.4.2) holds. Fix $\delta > 0$. For every positive integer k , there exists a positive integer n_k such that $n \geq n_k$ implies

$$\mu \left[\bigcup_{m=n}^{\infty} E_m \left(\frac{1}{k} \right) \right] < \frac{\delta}{2^k}.$$

By subadditivity and monotonicity,

$$\begin{aligned}\mu(F) &= \mu \left[\bigcup_{k=1}^{\infty} \bigcap_{n=1}^{\infty} \bigcup_{m=n}^{\infty} E_m \left(\frac{1}{k} \right) \right] \leq \sum_{k=1}^{\infty} \mu \left[\bigcap_{n=1}^{\infty} \bigcup_{m=n}^{\infty} E_m \left(\frac{1}{k} \right) \right] \\ &\leq \sum_{k=1}^{\infty} \mu \left[\bigcup_{m=n_k}^{\infty} E_m \left(\frac{1}{k} \right) \right] < \sum_{k=1}^{\infty} \frac{\delta}{2^k} = \delta.\end{aligned}$$

Since δ was arbitrary, $\mu(F) = 0$, and it follows that $f_n \rightarrow f$ a.e.

Conversely, suppose $f_n \rightarrow f$ a.e., so that $\mu(F) = 0$. By monotonicity and Theorem 1.2.2,

$$0 = \mu(F) = \mu \left[\bigcup_{k=1}^{\infty} \overline{\lim}_n E_n \left(\frac{1}{k} \right) \right] \geq \mu \left[\overline{\lim}_n E_n \left(\frac{1}{l} \right) \right] \geq \overline{\lim}_n \mu \left[E_n \left(\frac{1}{l} \right) \right]$$

for all positive integers l . But of course $\overline{\lim}_n \mu [E_n (1/l)] \geq \underline{\lim}_n \mu [E_n (1/l)] \geq 0$ since μ is nonnegative, so $\lim_n \mu [E_n (1/l)]$ exists and is equal to zero. Note that the sets $\bigcup_{m=n}^{\infty} E_m (1/l)$ are decreasing, so their limit as $n \rightarrow \infty$ exists. Hence we can apply Corollary 1.2.3 and monotonicity to find that

$$\begin{aligned}\lim_n \mu \left[\bigcup_{m=n}^{\infty} E_m \left(\frac{1}{l} \right) \right] &= \mu \left[\lim_n \bigcup_{m=n}^{\infty} E_m \left(\frac{1}{l} \right) \right] = \mu \left[\bigcap_{n=1}^{\infty} \bigcup_{m=n}^{\infty} E_m \left(\frac{1}{l} \right) \right] \\ &\leq \mu \left[\bigcup_{k=1}^{\infty} \bigcap_{n=1}^{\infty} \bigcup_{m=n}^{\infty} E_m \left(\frac{1}{k} \right) \right] = \mu(F) = 0.\end{aligned}$$

Finally, given $\epsilon > 0$, note that

$$E_n(\epsilon) \subset E_n \left(\frac{1}{\lceil 1/\epsilon \rceil} \right).$$

Hence

$$\lim_n \mu \left[\bigcup_{m=n}^{\infty} E_m(\epsilon) \right] \leq \lim_n \mu \left[\bigcup_{m=n}^{\infty} E_m \left(\frac{1}{\lceil 1/\epsilon \rceil} \right) \right] \leq 0$$

by monotonicity, and (2.4.2) follows.

2.4.4

Let X be the set of all positive integers, \mathcal{A} the class of all subsets of X , and $\mu(E)$ (for any $E \in \mathcal{A}$) the number of points in E . Prove that in this measure space, convergence in measure is equivalent to uniform convergence.

Solution. Uniform convergence always implies convergence in measure. Conversely, suppose (f_n) converges in measure to f . Given any $\epsilon > 0$, there exists a positive integer N such that $n \geq N$ implies

$$\mu [\{x; |f_n(x) - f(x)| \geq \epsilon\}] < 1.$$

That is, for $n \geq N$ the set $\{x; |f_n(x) - f(x)| \geq \epsilon\}$ is empty, which in particular means that $\sup_x |f_n(x) - f(x)| \leq \epsilon$. It follows that $f_n \rightarrow f$ uniformly.

Section 2.5 – Integrals of Simple Functions

Problems

2.5.2

An integrable simple function f is equal a.e. to zero if and only if $\int_E f d\mu = 0$ for any measurable set E .

Solution. Let f be an integrable simple function. Then f can be written in the form

$$f = \sum_{i=1}^n \alpha_i \chi_{E_i},$$

for mutually disjoint sets E_1, \dots, E_n , with all $\alpha_i \neq 0$, and all $\mu(E_i) < \infty$.

Suppose $f = 0$ a.e., and let E be any measurable set. By Theorem 2.5.1(b) and (g),

$$0 \leq \int_E f d\mu \leq \int f d\mu = \sum_{i=1}^n \alpha_i \mu(E_i).$$

But $\mu(E_i) = 0$ since $f = 0$ a.e., so $\int_E f d\mu = 0$.

Conversely, suppose $\int_E f d\mu = 0$ for all measurable sets E . Then

$$\alpha_i \mu(E_i) = \int_{E_i} f d\mu = 0,$$

so that $\mu(E_i) = 0$, for all $i \in \{1, \dots, n\}$. It follows that $f = 0$ a.e.

Section 2.6 – Definition of the Integral

Problems

2.6.3

Let f be a measurable function. Prove that f is integrable if and only if f^+ and f^- are integrable, or if and only if $|f|$ is integrable.

Solution. Let f be measurable. We must prove the equivalence of the following statements:

- (i) f is integrable.
- (ii) f^+ and f^- are integrable.
- (iii) $|f|$ is integrable.

We will first show that (iii) \implies (ii), then that (ii) \implies (i), and finally that (i) \implies (iii).

Suppose that $|f|$ is integrable. Let $E = \{x; f(x) \geq 0\} = f^{-1}[0, \infty)$, and note that E is measurable since f is. There exists a Cauchy in the mean sequence (g_n) of integrable simple functions converging to $|f|$ a.e., and the sequence $(\chi_E g_n)$

is easily seen to satisfy the corresponding properties with respect to f^+ . Since f^+ is measurable by Problem 2.1.8, this implies that it is integrable. The proof that f^- is integrable is similar.

Next, suppose that f^+ and f^- are integrable. Then there exist Cauchy in the mean sequences (g_n) and (h_n) of integrable simple functions converging a.e. to f^+ and f^- , respectively. Define a new sequence (f_n) of integrable simple functions by $f_n = g_n - h_n$. Then (f_n) is Cauchy in the mean, since

$$|f_n - f_m| = |g_n - h_n - g_m + h_m| \leq |g_n - g_m| + |h_n - h_m|.$$

It also converges to f a.e. since

$$|f_n - f| = |g_n - h_n - f^+ + f^-| \leq |g_n - f^+| + |h_n - f^-|.$$

It follows that f is integrable.

Finally, assume that f is integrable. There is a Cauchy in the mean sequence (f_n) of integrable simple functions converging to f a.e. The sequence $(|f_n|)$ consists of integrable simple functions. It is Cauchy in the mean since

$$||f_n| - |f_m|| \leq |f_n - f_m|,$$

and it converges to $|f|$ a.e. since

$$||f_n| - |f|| \leq |f_n - f|.$$

Since $|f|$ is measurable by Problem 2.1.9, it follows that $|f|$ is integrable.

2.6.4

Let X be the measure space described in Problem 2.4.4. Then f is integrable if and only if the series $\sum_{n=1}^{\infty} |f(n)|$ is convergent. If f is integrable, then

$$\int f d\mu = \sum_{n=1}^{\infty} f(n).$$

Solution. Suppose f is integrable. Then there is a Cauchy in the mean sequence (f_n) of integrable simple functions converging to f a.e. We saw in the previous problem that this implies that $|f|$ is integrable, and that $(|f_n|)$ is a Cauchy in the mean sequence of integrable simple functions converging to $|f|$ a.e. Note that in this particular space convergence a.e. is the same as convergence everywhere (since the only subset with measure zero is \emptyset).

By Theorem 2.5.1(h),

$$\int |f_n| d\mu = \sum_{i=1}^{\infty} \int_{\{i\}} |f_n| d\mu = \sum_{i=1}^{\infty} |f_n(i)|.$$

Hence, in particular,

$$\int |f| d\mu = \lim_{n \rightarrow \infty} \sum_{i=1}^{\infty} |f_n(i)|.$$

Given any positive integer m , there exists n' such that

$$|f(i) - f_{n'}(i)| < 1/m \quad (i = 1, 2, \dots, m)$$

(since $f_n \rightarrow f$) and

$$\left| \sum_{i=1}^{\infty} |f_{n'}(i)| - \int |f| d\mu \right| < 1$$

(since $\sum_i |f_n(i)| \rightarrow \int |f| d\mu$). Thus

$$\sum_{i=1}^m |f(i)| \leq \sum_{i=1}^m |f(i) - f_{n'}(i)| + \sum_{i=1}^m |f_{n'}(i)| < 1 + \sum_{i=1}^{\infty} |f_{n'}(i)| < 2 + \int |f| d\mu,$$

and it follows that the series $\sum_{i=1}^{\infty} |f(i)|$ converges (to a finite number).

Conversely, assume that the series $\sum_{i=1}^{\infty} |f(i)|$ converges. Define a sequence of integrable simple functions (g_n) by

$$g_n = \sum_{i=1}^n f(i) \chi_{\{i\}}.$$

It is clear that $g_n \rightarrow f$ everywhere. Moreover, if $m > n$, then

$$\int |g_m - g_n| d\mu = \int \left| \sum_{i=n+1}^m f(i) \chi_{\{i\}} \right| d\mu = \sum_{i=n+1}^m |f(i)| \leq \sum_{i=n+1}^{\infty} |f(i)|.$$

The right-hand side goes to zero as $n \rightarrow \infty$ since $\sum_{i=1}^{\infty} |f(i)|$ is convergent, which means that $\int |g_m - g_n| d\mu \rightarrow 0$ as $n, m \rightarrow \infty$; i.e., (g_n) is Cauchy in the mean. It follows that f is integrable, with

$$\int f d\mu = \lim_{n \rightarrow \infty} \int g_n d\mu = \lim_{n \rightarrow \infty} \sum_{i=1}^n f(i) = \sum_{i=1}^{\infty} f(i).$$

Chapter 3 – Metric Spaces

Section 3.1 – Topological and Metric Spaces

Problems

3.1.1

Prove that if (X, ρ) is a metric space, and if

$$\hat{\rho}(x, y) = \frac{\rho(x, y)}{1 + \rho(x, y)},$$

then also $(X, \hat{\rho})$ is a metric space. [*Hint:* Cf. the proof of (3.1.3).]

Solution. The only nonobvious property is the triangle inequality. Let x, y, z be arbitrary points of X . Since $t \mapsto t/(1+t)$ is monotone increasing on $[0, \infty)$, and since $\rho(x, z) \leq \rho(x, y) + \rho(y, z)$, we have

$$\frac{\rho(x, z)}{1 + \rho(x, z)} \leq \frac{\rho(x, y) + \rho(y, z)}{1 + \rho(x, y) + \rho(y, z)}.$$

Moreover, by equation (3.1.3),

$$\frac{\rho(x, y) + \rho(y, z)}{1 + \rho(x, y) + \rho(y, z)} \leq \frac{\rho(x, y)}{1 + \rho(x, y)} + \frac{\rho(y, z)}{1 + \rho(y, z)}.$$

It follows that $\hat{\rho}(x, z) \leq \hat{\rho}(x, y) + \rho(y, z)$.

3.1.2

Let $X, \rho, \hat{\rho}$ be as in Problem 3.1.1. Prove that $\rho(x_n, x) \rightarrow 0$ if and only if $\hat{\rho}(x_n, x) \rightarrow 0$. Give an example showing that ρ and $\hat{\rho}$ are not equivalent in general.

Solution. It is clear that $\rho(x_n, x) \rightarrow 0$ implies $\hat{\rho}(x_n, x) \rightarrow 0$, since $\hat{\rho} \leq \rho$.

Conversely, suppose $\hat{\rho}(x_n, x) \rightarrow 0$. Given any $\epsilon > 0$, there is a positive integer N such that

$$\hat{\rho}(x_n, x) < \frac{\epsilon}{1 + \epsilon} \quad (n \geq N).$$

Substituting the definition of $\hat{\rho}$ and rearranging yields $\rho(x_n, x) < \epsilon$.

If ρ and $\hat{\rho}$ are equivalent then, in particular, there exists a positive constant β such that

$$\frac{\rho(x, y)}{\hat{\rho}(x, y)} \leq \beta$$

whenever $x \neq y$. But

$$\frac{\rho(x, y)}{\hat{\rho}(x, y)} = 1 + \rho(x, y),$$

so this is impossible if X is unbounded (w.r.t. ρ), say if $X = \mathbb{R}^n$ and ρ is the Euclidean metric.

3.1.6

Prove that the spaces l^1, s, c, c_0 are separable metric spaces.

Solution. For each of the spaces X we will take an arbitrary element $x \in X$ and demonstrate that every ϵ -ball around x contains a point y of a certain countable subset $Y \subset X$. It will then follow that Y is dense in X , and hence that X is separable.

Let $x = (x_i) \in l^1$. Fix $\epsilon > 0$. Since $\sum_i |x_i| < \infty$, there exists n such that

$$\sum_{i=n+1}^{\infty} |x_i| < \frac{\epsilon}{2}.$$

For $i = 1, \dots, n$, choose $y_i \in \mathbb{Q}$ (or y_i with rational real and imaginary parts in the complex case) such that $|x_i - y_i| < \epsilon/2n$, and let $y = (y_1, \dots, y_n, 0, 0, \dots)$. Then

$$\rho(x, y) = \sum_{i=1}^n |x_i - y_i| + \sum_{i=n+1}^{\infty} |x_i| < \epsilon.$$

Moreover, y is an element of the subset of l^1 consisting of sequences with rational components, with only finitely many being nonzero. This subset is easily seen to be countable, and it follows that l^1 is separable.

Next, let $x = (x_i) \in s$, and fix $\epsilon > 0$. Choose n such that

$$\sum_{i=n+1}^{\infty} \frac{1}{2^i} \frac{|x_i|}{1 + |x_i|} < \frac{\epsilon}{2}.$$

For $i = 1, \dots, n$, choose $y_i \in \mathbb{Q}$ such that $|x_i - y_i| < \epsilon/2$, and let $y = (y_1, \dots, y_n, 0, 0, \dots)$. Then

$$\rho(x, y) = \sum_{i=1}^n \frac{1}{2^i} \frac{|x_i - y_i|}{1 + |x_i - y_i|} + \sum_{i=n+1}^{\infty} \frac{1}{2^i} \frac{|x_i|}{1 + |x_i|} < \epsilon.$$

Similarly to the above, it follows that s is dense.

Finally, let $x = (x_i) \in c$. (This argument will also cover c_0 .) Let $\xi = \lim_i x_i$ and fix $\epsilon > 0$. Choose n such that $|x_i - \xi| < \epsilon/2$ for all $i \geq n$. For $i = 1, \dots, n-1$,

choose $y_i \in \mathbb{Q}$ such that $|x_i - y_i| < \epsilon$. Also choose $\eta \in \mathbb{Q}$ such that $|\xi - \eta| < \epsilon/2$ (take $\eta = \xi = 0$ in the c_0 case), so that

$$|x_i - \eta| \leq |x_i - \xi| + |\xi - \eta| < \epsilon$$

for all $i \geq n$. Let $y = (y_1, \dots, y_{n-1}, \eta, \eta, \dots)$. Then

$$\rho(x, y) = \sup_i |x_i - y_i| \leq \epsilon.$$

It follows that c is separable (and c_0 as well).

3.1.10

If $\rho(x_n, x) \rightarrow 0$, $\rho(y_n, y) \rightarrow 0$, then $\rho(x_n, y_n) \rightarrow \rho(x, y)$.

Solution. The triangle inequality yields

$$\rho(x_n, y_n) \leq \rho(x_n, x) + \rho(x, y) + \rho(y, y_n)$$

and

$$\rho(x, y) \leq \rho(x, x_n) + \rho(x_n, y_n) + \rho(y_n, y).$$

Hence

$$|\rho(x_n, y_n) - \rho(x, y)| \leq \rho(x_n, x) + \rho(y_n, y),$$

and the result follows.

Section 3.2 – L^p Spaces

Problems

3.2.4

Prove that l^p is separable if $1 \leq p < \infty$.

Solution. The argument is of the same sort as in Problem 3.1.6. Given $x = (x_i) \in l^p$ ($1 \leq p < \infty$) and $\epsilon > 0$, choose n such that

$$\sum_{i=n+1}^{\infty} |x_i|^p < \frac{\epsilon^p}{2}.$$

(This is possible since $\sum_i |x_i|^p < \infty$ for $x \in l^p$.) For $i = 1, \dots, n$, choose $y_i \in \mathbb{Q}$ such that $|x_i - y_i|^p < \epsilon^p/2n$ and let $y = (y_1, \dots, y_n, 0, 0, \dots)$. Then $\|x - y\|_p < \epsilon$, and the conclusion follows as in Problem 3.1.6.

3.2.5

Prove that l^p is not a metric space if $0 < p < 1$.

Solution. Let $x = (1, 0, 0, \dots)$, $y = (0, 0, \dots)$, $z = (0, 1, 0, 0, \dots)$. Then

$$\|x - z\|_p = 2^{1/p}$$

while

$$\|x - y\|_p + \|y - z\|_p = 2.$$

But $2^{1/p} > 2$ if $0 < p < 1$, so the triangle inequality does not hold.

3.2.6

Prove that the space $C[a, b]$ with the metric

$$\rho(f, g) = \int_a^b |f(t) - g(t)| dt$$

is not a complete metric space.

Solution. Note that the integral defining ρ is guaranteed to exist by Theorem 2.11.1 and the extreme value theorem from elementary analysis, and it can be taken in the Riemann sense. It is easily seen that ρ is indeed a metric.

For simplicity, let us assume $a = 0$ and $b = 1$. (The general argument is identical modulo a coordinate transformation.) Define a sequence of functions in $C[0, 1]$ by $f_n(x) = x^n$. Clearly (f_n) converges pointwise to the discontinuous function

$$f(x) = \begin{cases} 0 & (0 \leq x < 1), \\ 1 & (x = 1). \end{cases}$$

For $n \geq m$ we have $f_n \geq f_m$, hence

$$\rho(f_n, f_m) = \int_0^1 f_n(t) dt - \int_0^1 f_m(t) dt = \frac{1}{n+1} - \frac{1}{m+1},$$

which goes to zero as $n, m \rightarrow \infty$. Thus (f_n) is a Cauchy sequence in $C[0, 1]$ which converges to a function f which is not in $C[0, 1]$, so $(C[0, 1], \rho)$ is not a complete metric space.

Section 3.4 – Complete Metric Spaces

Problems

3.4.5

A set Y in a metric space X is said to be *of the first category in X* if it is contained in a countable union of nowhere dense sets of X . If Y is not of the first category in X , then it is said to be *of the second category in X* . The real line with the Euclidean metric is a space of the second category. Prove, however, that, as a subset of the Euclidean plane, the real line is a set of the first category.

Solution. We identify the real line with the subset $L = \{(x, y) \in \mathbb{R}^2 : y = 0\}$, with the induced metric topology. Indeed L is homeomorphic to \mathbb{R} via the map $(x, 0) \mapsto x$, as can easily be shown.

The sets of the form $B((0, 0), r) \cap L = \{(x, 0) : |x| < r\}$ are easily seen to be nowhere dense in \mathbb{R}^2 , and we have

$$L = \bigcup_{n=1}^{\infty} B((0, 0), n) \cap L.$$

Hence L is of the first category in \mathbb{R}^2 .

3.4.7

Let $f(x)$ be a real-valued function on the real line. Prove that there is a nonempty interval (a, b) and a positive number c such that for any $x \in (a, b)$ there is a sequence $\{x_n\}$ such that $x_n \rightarrow x$ and $|f(x_n)| \leq c$.

Solution. Note that

$$\mathbb{R} = |f|^{-1}(\mathbb{R}) = |f|^{-1}\left(\bigcup_{n=1}^{\infty} (-\infty, n]\right) = \bigcup_{n=1}^{\infty} |f|^{-1}((-\infty, n]).$$

Since \mathbb{R} is of the second category (by Theorem 3.4.2), the sets $|f|^{-1}((-\infty, n])$ cannot all be nowhere dense. Hence there is a positive integer c such that the closure of $|f|^{-1}((-\infty, c])$ has nonempty interior. On account of being a nonempty open set, this interior contains an open interval (a, b) .

Let $x \in (a, b)$. Then, since x is contained in the closure of $|f|^{-1}((-\infty, c])$, every neighborhood of x contains a point of $|f|^{-1}((-\infty, c])$. It follows that we can construct a sequence (x_n) in $|f|^{-1}((-\infty, c])$ converging to x , and this sequence will satisfy $|f(x_n)| \leq c$ for all n .

Section 3.5 – Compact Metric Spaces

Problems

3.5.4

A subset F of a compact metric space is compact if and only if it is closed.

Solution. Let X be a compact metric space, and F a subset of X . If F is compact then it is also closed by Corollary 3.5.5.

Conversely, suppose that F is closed. Let \mathcal{C} be any open cover of F . The collection $\mathcal{C} \cup \{X - F\}$ is an open cover of X , hence it has a finite subcover, consisting of some sets $E_1, \dots, E_n \in \mathcal{C}$ and perhaps $\{X - F\}$. The sets E_1, \dots, E_n cover F , hence F is compact.

3.5.5

A subset Y of a metric space is totally bounded if and only if its closure \overline{Y} is totally bounded.

Solution. Clearly Y is totally bounded whenever \overline{Y} is. Conversely, suppose Y is totally bounded, and let $\epsilon > 0$ be given. Then Y admits a finite $\epsilon/2$ -covering,

$$\{B(x_1, \epsilon/2), \dots, B(x_n, \epsilon/2)\}.$$

The union of the closed balls,

$$\bigcup_{i=1}^n \overline{B}(x_i, \epsilon/2),$$

is a closed set containing Y , hence it contains \overline{Y} . It follows that

$$\overline{Y} \subset \bigcup_{i=1}^n \overline{B}(x_i, \epsilon/2) \subset \bigcup_{i=1}^n B(x_i, \epsilon),$$

so \overline{Y} admits a finite ϵ -covering.

3.5.6

The intersection of any number of compact subsets of a metric space is a compact space.

Solution. Let \mathcal{C} be a collection of compact subsets of a metric space X . By Corollary 3.5.5 each $C \in \mathcal{C}$ is closed, hence the intersection $K = \bigcap \mathcal{C}$ is closed as well. Let C' be some particular member of \mathcal{C} . Then K is a closed subset of the compact space C' , thus itself compact by Problem 3.5.4.

Remark: Really the above shows that K is compact *in* C' . However, one easily proves the general result that if F is compact in G , and G is compact in H , then F is compact in H . Hence K is indeed compact in X .

3.5.8

Show that a metric space is compact if and only if it has the following property: for every collection of closed subsets $\{F_\alpha\}$, if any finite subcollection has nonempty intersection, then the whole collection has a nonempty intersection.

Solution. The wording of the problem is potentially misleading. Replace “any” with “every” to make it nonambiguous. Also, let us introduce some useful terminology. A collection of subsets of a topological space is said to have the *finite intersection property* iff every finite subcollection has nonempty intersection. Our task is therefore to show that a metric space X is compact iff every collection \mathcal{F} of closed subsets of X having the finite intersection property has nonempty intersection. However, the proof we will use is valid for general topological spaces, not just metric spaces.

Let X be a topological space, and suppose first that X is compact. Let \mathcal{F} be a collection of closed subsets of X with the finite intersection property. Assume towards a contradiction that $\bigcap \mathcal{F} = \emptyset$. Then

$$\bigcup_{F \in \mathcal{F}} (X - F) = X - \bigcap_{F \in \mathcal{F}} F = X,$$

so $\{X - F; F \in \mathcal{F}\}$ is an open cover of X . Since X is compact, there are sets $F_1, \dots, F_n \in \mathcal{F}$ such that

$$X = \bigcup_{i=1}^n (X - F_i) = X - \bigcap_{i=1}^n F_i.$$

But then $\bigcap_{i=1}^n F_i = \emptyset$, contradicting the hypothesis that \mathcal{F} has the finite intersection property. We conclude that $\bigcap \mathcal{F} \neq \emptyset$.

Conversely, suppose that X has the property described in the problem statement: every collection of closed subsets of X with the finite intersection property has nonempty intersection. Let \mathcal{U} be any open cover of X , and assume towards a contradiction that \mathcal{U} has no finite subcover. Then

$$\bigcap_{i=1}^n (X - U_i) = X - \bigcup_{i=1}^n U_i \neq \emptyset$$

for every finite subcollection $\{U_1, \dots, U_n\} \subset \mathcal{U}$. Hence $\mathcal{F} = \{X - U; U \in \mathcal{U}\}$ is a collection of closed subsets with the finite intersection property. By hypothesis \mathcal{F} has nonempty intersection, so

$$\emptyset = X - \bigcup_{U \in \mathcal{U}} U = \bigcap_{U \in \mathcal{U}} (X - U) = \bigcap_{F \in \mathcal{F}} F \neq \emptyset,$$

a contradiction. We conclude that \mathcal{U} does indeed have a finite subcover, and that X is compact.